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Development of New TOYOTA FCHV-adv

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Abstract

Toyota began leasing the TOYOTA FCHV in Japan and the U.S. in December 2002, a world first for a fuel cell vehicle. Subsequently, in June 2008, Toyota obtained model certification in Japan for its new fuel cell hybrid vehicle, the TOYOTA FCHV-adv. This vehicle is currently being leased on a limited scale in Japan and the U.S. In addition to a substantially longer cruising range, the TOYOTA FCHV-adv features major improvements in start and dynamic performance in subfreezing temperatures. As a result, it has an actual cruising range equivalent to a conventional gasoline vehicle of 500 km, and can be started and driven in cold environments up to -30°C. This paper describes an outline of the TOYOTA FCHV-adv.

Keywords: fuel cell, vehicle performance, range, reliability, efficiency

1 Introduction

1.1 FCHV Development in Toyota

Following the principle of "the right vehicle in the right place and at the right time," Toyota Motor Corporation is working to develop various types of advanced transportation technologies that contribute to the development of a society in which people and the global environment can exist in harmony, in other words, a society achieving sustainable mobility. One technology that is recognized as having significant potential for the future is the fuel cell vehicle (FCV). Toyota began fuel cell development in 1992, and was the first company in the world to begin leasing an FCV (the TOYOTA FCHV) in 2002. In 2005, Toyota obtained model certification for a revised version of this vehicle that complied with the Japanese government's new safety standards. Subsequently, in 2008, Toyota announced and began leasing the TOYOTA FCHV-adv, which features major improvements in cruising range, cold start capability, and durability (Table 1).

Table1: FCHV Model Development

	2002 TOYOTA FCHV	2005 TOYOTA FCHV	2008 TOYOTA FCHV-adv
Dynamic performance	Good	Good	Good
Reliability	-	Good	Good
Cruising range	-	-	Good
Cold start capability	-	-	Good
Cost	-	-	-

Table 2 shows the placement of Toyota's FCHVs. Starting with the introduction of the TOYOTA FCHV-adv to Japan in September 2008 and to the U.S. in January 2009, the total number of vehicles currently undergoing actual road testing is gradually being increased.

Table2: FCHV Model Placement

		Japan	U.S.	Total
Leased vehicles	2002 TOYOTA FCHV	11	7	18
	2005 TOYOTA FCHV	11	9	20
	2008 TOYOTA FCHV-adv	14	From 2009	
	Subtotal	35	-	-
Certified test vehicles		24		
Total		60		

Before the TOYOTA FCHV-adv was introduced into the market, test vehicles were certified by the Japanese government in December 2006. Actual vehicle tests were then performed on public roads in Japan, the U.S., and Canada. These tests verified the improvements in vehicle performance related to cruising range, cold start capability, and the like.

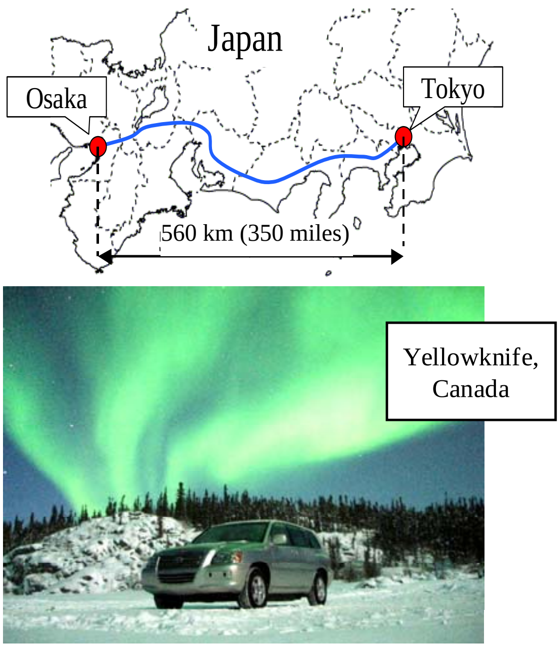

Figure1: Public Road Evaluations of Test Vehicles (Top: Long Distance Osaka-Tokyo Road Test without Refueling; Bottom: Cold Weather Evaluations in North America)

As part of these tests, the TOYOTA FCHV-adv successfully completed a long distance road test by traveling from Osaka to Tokyo (approximately 560 km) without refueling. Cold weather evaluations were also performed in Hokkaido, the U.S., and Canada, which verified that the vehicle could be started and driven in temperatures as low as -37°C (Fig.1).

1.2 New TOYOTA FCHV-adv

Figure 2 and Table 3 shows the appearance and specifications of the TOYOTA FCHV-adv. Figure 3 shows an outline of the fuel cell (FC) system.

Figure2: TOYOTA FCHV-adv

Table 3: Specifications of TOYOTA FCHV-adv

Vehicle		TOYOTA FCHV-adv	TOYOTA FCHV
Overall length/width/height		4,735/1,815/1,685	4,735/1,815/1,685
Weight (kg)		1880	1880
Seating capacity		5	5
Maximum cruising range (km)* 10-15 test cycle/JC08 test cycle		Approx. 830/Approx. 760	Approx. 330/-
Maximum speed (km/h)		155	155
Fuel Cell	Name	Toyota FC Stack	Toyota FC Stack
	Type	Polymer electrolyte	Polymer electrolyte
	Output (kW)	90	90
Motor	Type	Permanent magnet	Permanent magnet
	Maximum output in kW (ps)	90 (122)	90 (122)
	Maximum Torque in N-m (kg-m)	260 (26.5)	260 (26.5)
Fuel		Hydrogen	Hydrogen
Storage system		High-pressure storage tanks	High-pressure storage tanks
Maximum storage pressure (MPa)		70	35
Tank capacity (L)		156	148
Battery		Nickel-metal hydride	Nickel-metal hydride

*As based on TMC calculations

The FC system of the TOYOTA FCHV-adv consists of an FC stack, in combination with subsystems for supplying hydrogen and air, and cooling.

Hydrogen is supplied from the high-pressure 70 MPa tanks to the FC stack through multiple stages of regulation and finally through an injector. Unused hydrogen from the FC stack is recirculated by the hydrogen pump. All the parts for the TOYOTA FCHV-adv hydrogen recirculation system are provided compactly within the FC stack case.

An air compressor supplies air to the FC stack through the humidifier. The humidifier extracts water vapor (generated water) from the air outlet of the FC stack to increase the humidity of the air supplied to the FC stack to an optimum level. In accordance with the state of the FC stack, the humidifier of the TOYOTA FCHV-adv also includes a bypass valve that allows the supply of non-humidified dry air. The pressure of the supplied air is regulated based on the driving conditions by a regulator provided at the stack outlet. The air supply subsystem also features an air shut valve that is capable of sealing off the cathode of the FC stack after the FC system is shutdown. The cooling subsystem in the 2005 TOYOTA FCHV has been simplified by integrating the cooling systems for the supplied air and the FC stack.

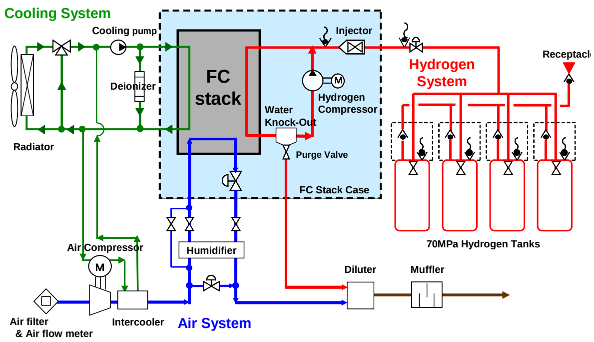

Figure3: Outline of FC System of TOYOTA FCHV-adv

2 Cruising Range

2.1 Target and Actual Cruising Range

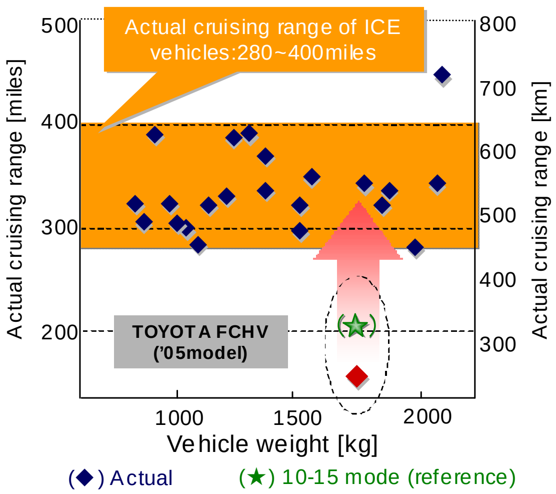

Figure4: Comparison of Actual Cruising Range

Figure 4 shows the actual cruising range of conventional gasoline vehicles and the 2005 TOYOTA FCHV. The actual cruising range is calculated based on the fuel capacity of the vehicles and actual fuel efficiency measured according to Toyota's in-house test cycle that simulates actual driving conditions. The figure indicates that an actual cruising range of more than 500 km (300 miles) is required to compete with gasoline vehicles.

In contrast, the 2005 TOYOTA FCHV achieved a cruising range of 330 km in the 10-15 cycle and an actual cruising range of approximately 220 km, which needed to be significantly improved.

Cruising range is a product of fuel efficiency and hydrogen storage capacity. Therefore, the actual cruising range can only be extended by (1) increasing the hydrogen storage capacity and (2) improving fuel efficiency. The following sections describe these improvements for the TOYOTA FCHV-adv.

Figure 5 analyzes the actual cruising range of the 2005 TOYOTA FCHV shown in Figure 4 based on hydrogen storage capacity and fuel efficiency. The curves in the graph show the gasoline-equivalent actual cruising range. It indicates that, although the FCHV already has better fuel efficiency than a gasoline vehicle in the same class, it has a much smaller fuel capacity.

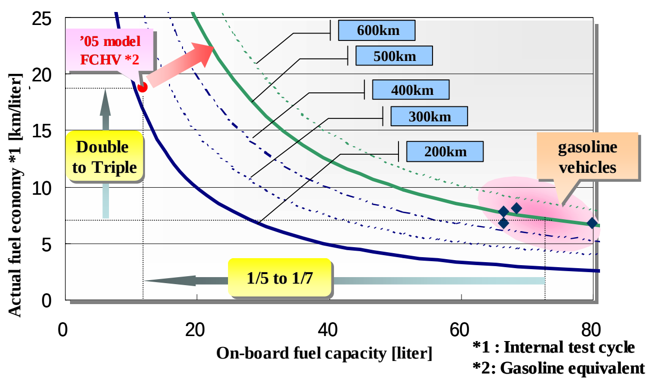

Figure5: Cruising Range Comparison

2.2 Increased Hydrogen Storage Capacity

The high-pressure tanks in the TOYOTA FCHV-adv are based on those used in previous models. It was realized that increasing the hydrogen storage capacity simply by boosting the filling pressure and internal volume would lead to major increases in tank weight and size. Therefore, the following improvements were made to achieve a higher hydrogen storage capacity without major impacts on the external volume or weight of the tanks (i.e., the packaging and performance of the vehicle). In

addition to increasing the filling pressure to 70 MPa, the carbon fiber layer was optimized to reduce its thickness, the tank valves were made smaller using new materials, and the amount of residual (unusable gas) was reduced.
As a result, although fuel capacity was improved greatly by 90%, increases in the external tank dimensions and weight were restricted to 21% and 13%, respectively (Fig.6).

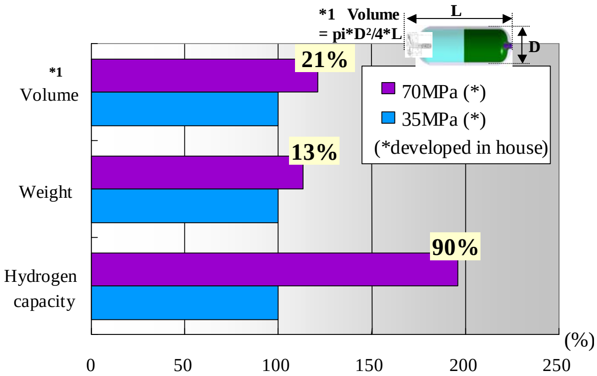

Figure6: Comparison of High-Pressure Hydrogen Tank Specifications

2.3 Improved Fuel Efficiency

Figure 7 shows a breakdown of the energy consumption of the 2005 TOYOTA FCHV in the LA#4 test cycle.

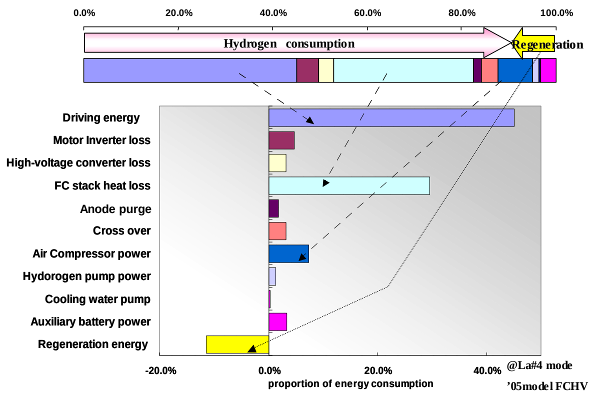

Figure7: Breakdown of Energy Consumption of 2005 TOYOTA FCHV

The amount of energy consumption during driving is equal to the hydrogen consumption of the vehicle plus regenerative brake energy. The breakdown shows that the energy required for driving is only a part of the total vehicle's energy consumption. In addition to FC stack loss, other major contributions to energy consumption include the power requirements of the air compressor, and the energy required by the high-voltage system.

As shown in Table 4, the TOYOTA FCHV-adv has improved virtually all the items that affect fuel efficiency.

Table 4: Fuel Efficiency Improvements in TOYOTA FCHV-adv

FC stack	Improved I-V performance
Hydrogen supply system	Supply pressure, flow rate, purge volume
Air supply system	Supply pressure and volume
Cooling system	Idle flow rate
High-voltage system	Converter control Regenerative brakes

As a result, the overall energy consumption of the TOYOTA FCHV-adv was reduced by 15%, and the regenerative energy recovered from braking was increased by 25% (Fig. 8). As shown in Figure 9, this equates to a fuel efficiency improvement of approximately 25%.

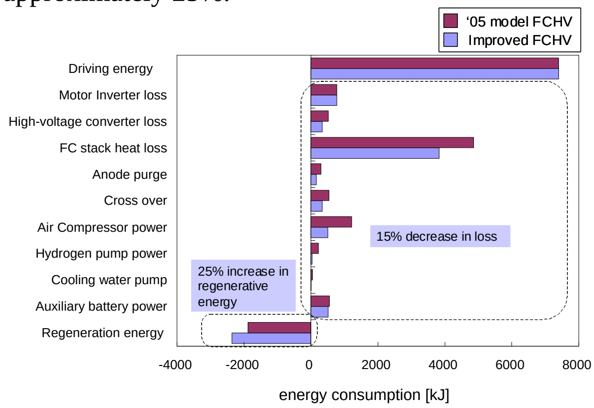

Figure8: Breakdown of Energy Consumption of TOYOTA FCHV-adv

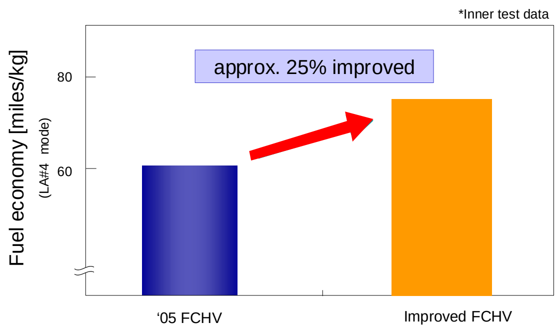

Figure9: Fuel Efficiency Comparison

Figure 10 shows the efficiency of the improved and conventional FC systems at various loads. The efficiency of the FC system in the TOYOTA FCHV-adv was improved to a maximum of 64 percent. This equates to a well-to-wheel efficiency of approximately 40%, around twice that of a gasoline vehicle (Fig.11).

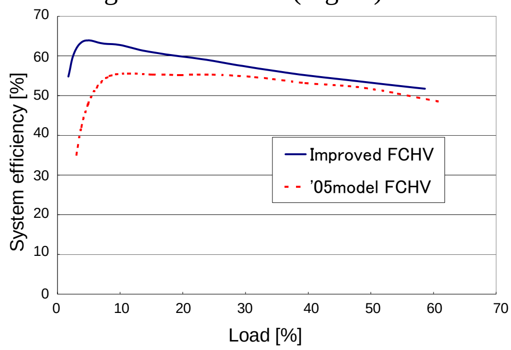

Figure10: FC System Efficiency Comparison

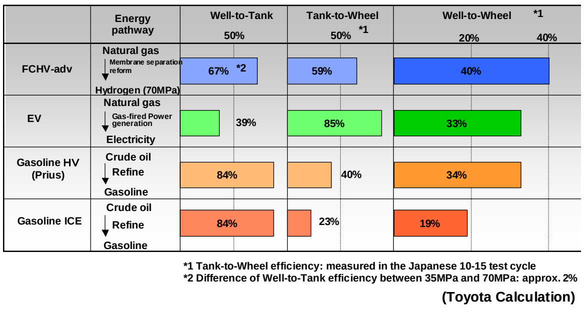

Figure11: Comparison of Total Energy Efficiency

2.4 Cruising Range of TOYOTA FCHV-adv

The cruising range of the TOYOTA FCHV-adv is approximately 2.5 times longer than that of the 2005 TOYOTA FCHV. This was achieved by substantially improving fuel efficiency through FC system efficiency improvements, and by increasing the hydrogen storage capacity through adopting new high-pressure 70 MPa hydrogen tanks.

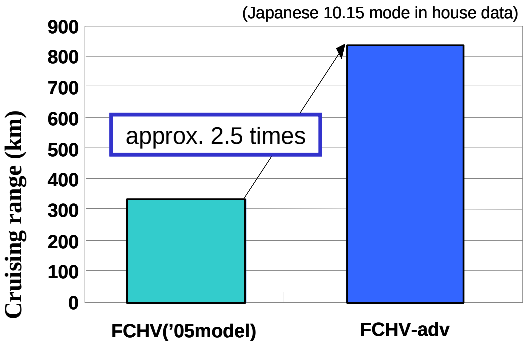

Figure12: Cruising Range Comparison

If the cruising range is analyzed according to test cycle, the TOYOTA FCHV-adv achieves over 500 km in the actual driving cycle, 830 km in the 10-15 cycle, and 790 km in the LA#4 cycle. This is the highest cruising range of any FCV in the world.

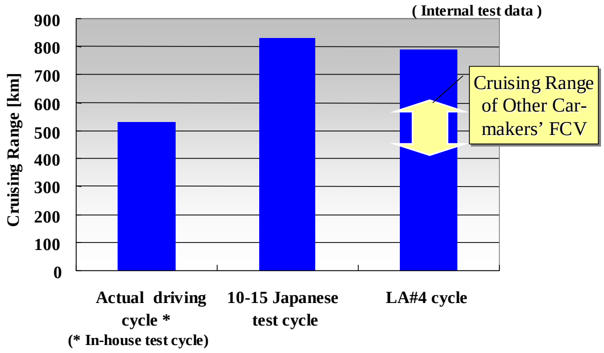

Figure13: Cruising Range of TOYOTA FCHV-adv in Each Test Cycle

3 Cold Start Capability

In addition to cruising range, cold start capability is one of the major issues confronting FCVs. The following sections describe the efforts to improve the cold start capability of the TOYOTA FCHV-adv.

3.1 Improved FC Startability

To start the FC system at subfreezing temperatures, it is important to control the generated water to prevent it from freezing. This water, which accumulates in the FC membrane electrode gasket assembly (MEGA) and gas channels, freezes and reduces gas diffusion if left uncontrolled. This may prevent the continuation of power generation in the FC or cause operational defects of system components. Since many details of the freezing mechanism were unknown, the behavior of the generated water during power generation in freezing environments was visualized. This enabled the design of the FC cells and system to be optimized to prevent the FC or FC subsystems from freezing.

The visualization found that when the FC generates power at subfreezing temperatures, the generated water is initially super-cooled (Fig. 14) [3].

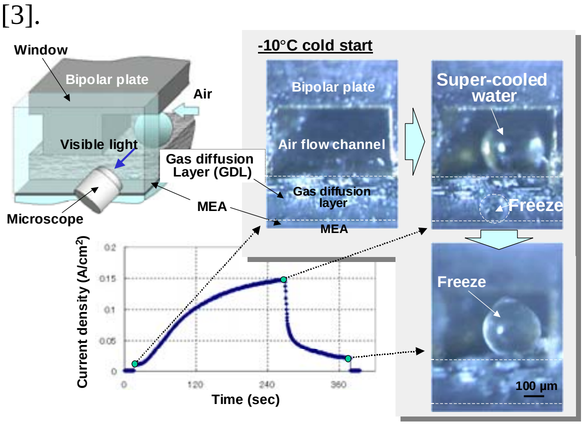

Figure14: Observation of Fuel Cell Cross Section

In addition, when power generation cannot be continued, it was found that gas exchange was being inhibited by the frozen generated water at the interfacial surface of the membrane electrode assembly (MEA) and the gas diffusion layer (GDL), dramatically reducing the power generation performance of the FC (Fig. 15) [3].

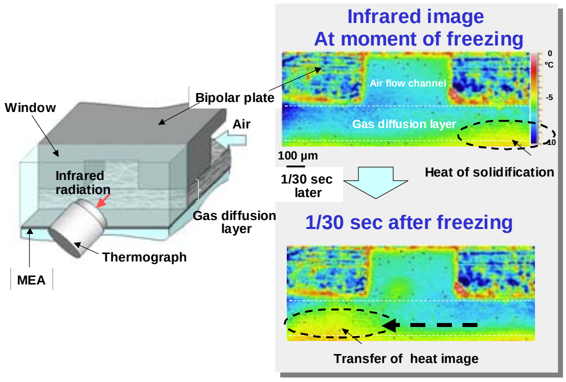

Figure15: Observation of MEA-GDL Interface Freezing Phenomenon

These observations demonstrated that the following measures would be necessary to start the FC and continue power generation at subfreezing temperatures: (1) the generated water must be kept in a super-cooled state and continually drained, and (2) the temperature must be increased to a point where power generation can be continued (i.e., above 0°C) before water drainage becomes impossible (i.e., in a short period of time).

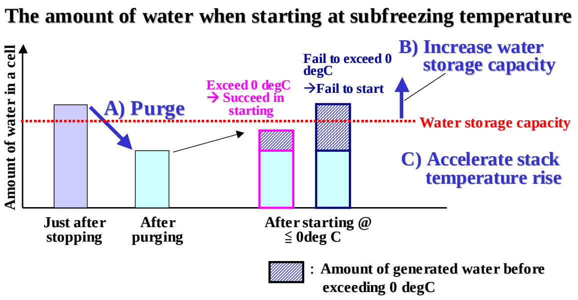

Figure16: Amount of Water in Cells During Cold Start

The first issue was addressed by clarifying the mechanism of super-cooling and freezing of the generated water at the interfacial surface of the MEA and GDL. This enabled optimization of the design for removing generated water and control of the amount of water present at the beginning of power generation (at the end of the previous driving operation). As a result, power generation performance at subfreezing temperatures was improved.

Figure 17 shows the measured current at a constant voltage and a constant temperature of -10°C. It shows an improvement in integrated current at the start of power generation.

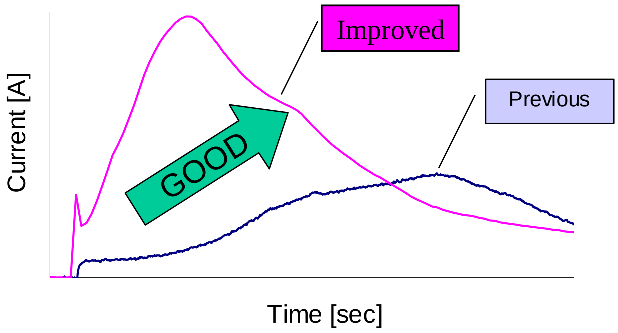

Figure17: Improvement of Current Performance Under –10°C

To warm up the FC above 0°C quickly after the start of power generation, it is important to increase the amount of generated power by improving the power generation performance described above. In other words, the amount of generated heat must be increased and the heat capacity must be reduced. Figure 17 shows that the heat capacity of the TOYOTA FCHV-adv has been reduced by 50%. Consequently, startability is improved as a result of the shorter warm-up time due to the reduction in heat capacity, and the synergistic effect created by the improved I-V characteristics due to the increase in temperature.

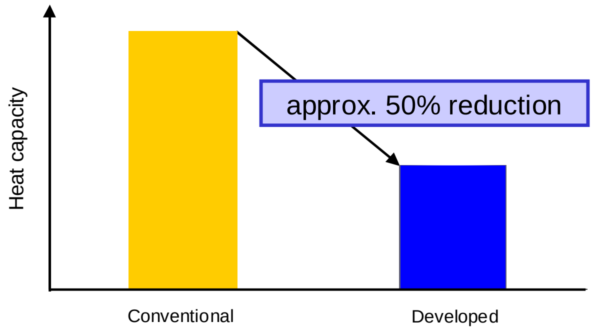

Figure18: Improvement of Current Performance

3.2 Enabling Cold Start of the FC System

As is the case with the FC, to continue power generation at subfreezing temperatures, it is important to prevent freezing and adhesion of the generated water in the FC system components. In the TOYOTA FCHV-adv, the hydrogen recirculation system and other components that are susceptible to freezing due to generated water are integrated into the FC stack case (Fig. 19). This structure maintains the temperature of the components above 0°C even when the vehicle is being driven in environments as low as -30°C.

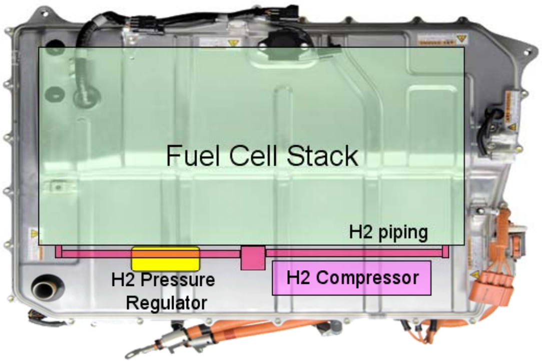

Figure19: Outline of Component Layout in FC Stack Case

3.3 Cold Start Capability

As shown in Figure 20, these improvements have enabled a start up time of 30 seconds at -20°C, which is the best cold start capability of any FCV in the world.

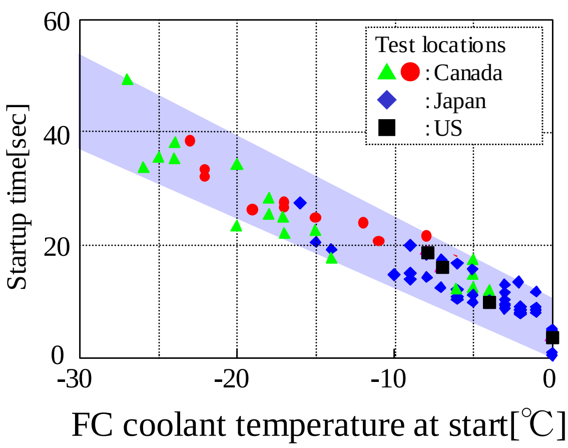

Figure20: Start-Up Time of TOYOTA FCHV-adv

However, further improvement is required from the standpoint of product quality. In particular, progress must be made in reducing both scavenging time when the vehicle stops and start-up time, and in improving durability after repeated cold starts.

4 Improved Durability

Durability of the FC stack is being gradually improved. As a result of various countermeasures against physical and chemical degradation to improve crossover, the durability of the FC stack is now equivalent to the lifetime of the vehicle. Additionally, the development of new materials for the MEGA and the adoption of a system-based approach have achieved significant progress against reductions in the output performance of the TOYOTA FCHV-adv. This section describes the analysis and adopted countermeasures against catalyst degradation after the system stops.

4.1 Carbon Oxidation

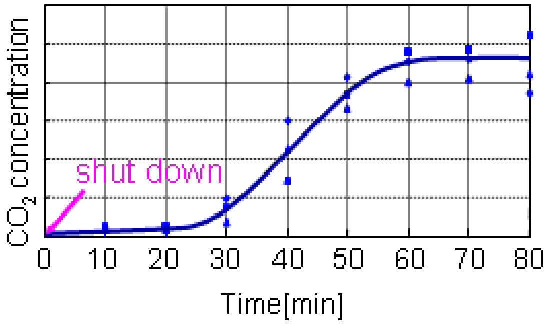

Figure21: CO_2 Generation After System Stoppage

Figure 21 shows an example of degradation mode analysis under actual use conditions. The graph uses measured CO_2 to show the oxidation of carbon loaded on the catalyst after the system stops.

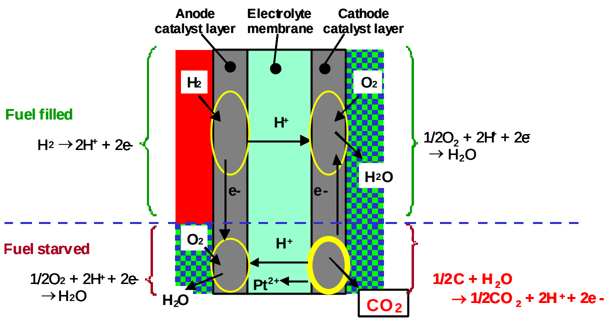

Figure22: Mechanism of Carbon Oxidation Due to Uneven Distribution of Gas

An increase in CO_2 concentration was observed thirty minutes after the system was shutdown. This is because the hydrogen and oxygen distribution on the anode became uneven due to crossover of air at the cathode and hydrogen at the anode. This results in an abnormal increase in potential at the cathode and causes cathode catalyst degradation (carbon oxidation) to advance (Fig. 22).

One countermeasure for this degradation mode in the TOYOTA FCHV-adv is the air shut valve provided in the air supply line at the FC stack inlet/outlet. When the system is stopped (i.e., when the vehicle is parked), the cathode line of the FC stack is sealed to control the permeation and diffusion of oxygen to the anode. This prevents oxidation of the carbon loaded on the catalyst due

to mixing of hydrogen and oxygen at the anode, thereby contributing to improved durability.
Sealing the cathode line also stabilizes FC operation immediately after start by controlling the permeation of non-hydrogen gaseous impurities from the cathode to the anode. This enables a high concentration of pure anode gas to be maintained for the next start-up.

4.2 Actual Vehicle Durability Tests

Figure 23 shows the changes in FC output in durability tests on public roads in the Japan and the U.S. It indicates that the TOYOTA FCHV-adv has an excellent durability performance. It is planned to continue the durability tests with the aim of achieving a limit performance greater than the lifetime of conventional vehicles.

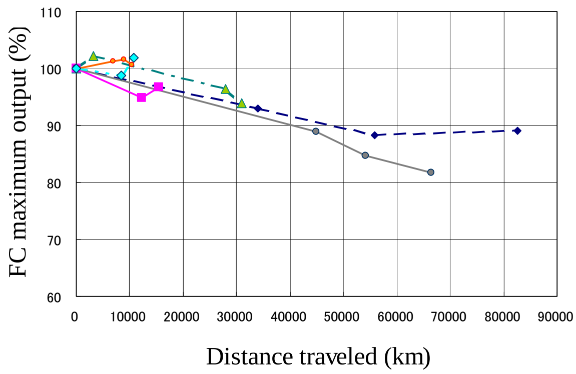

Figure23: FC Output Trend

5 Data Transfer System

The TOYOTA FCHV-adv also has a system that transfers vehicle performance data to a server at regular intervals. This data is used to confirm whether the vehicle is maintaining the same performance (e.g., real world fuel efficiency and cold start capability) as when it was developed, and to identify new technological issues.

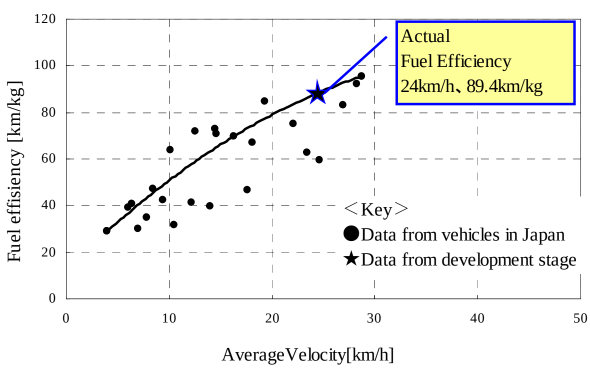

Figure24: Fuel Efficiency Analysis of Vehicles

Figure 24 shows an example data transfer using the results of fuel efficiency analysis. This data uses a total distance of 22,000km traveled from September 2008 to March 2009 for the 12 vehicles in Japan. Cold start capability and durability are also analysed. The analysis confirms that the TOYOTA FCHV-adv has maintained the same performance since its development.

6 Conclusion

Cruising range is a major issue for FCVs. To address this issue, the TOYOTA FCHV-adv has 1.9-times the hydrogen storage capacity of the 2005 TOYOTA FCHV and 25% improved fuel efficiency. As a result, the TOYOTA FCHV-adv has achieved an actual cruising range equivalent to a gasoline vehicle of 500 km, and a cruising range in the LA#4 test cycle of 790 km, which is the highest of any FCV in the world. For cold start capability, the TOYOTA FCHV-adv has also achieved the best startable temperature and start-up time in the world.
In addition, material- and system-based countermeasures were applied after analyzing the FC stack degradation phenomena under actual operating conditions. This has resulted in improved durability under actual use environments.
Many issues remain to be resolved before FCVs can be sold and popularized. It is particularly important to make progress toward reducing costs and achieving satisfactory levels of various aspects of product quality such as serviceability. However, the depletion of oil resources and CO_2 reduction are issues that require immediate attention, and it is imperative that industry, the government, and academia all work together to develop groundbreaking technological innovations for the issues highlighted in this paper.

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From 1999: Development of fuel cell vehicles.